PB90-112558

Minimization of Transient Emissions from Rotary Kiln Incinerators

Arizona Univ., Tucson

Prepared for:

Environmental Protection Agency, Research Triangle Park, NC

1989

U.S. Department of Commerce
National Technical Information Service
NTIS

AEERL-P-578

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completi

1. REPORT NO. EPA/600/D-89/131	2.	3. PB90-112558
4. TITLE AND SUBTITLE Minimization of Transient Emissions from Rotary Kiln Incinerators		5. REPORT DATE 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) P. Lemieux, W. Linak, J. McSorley (EPA/AEERL); J. Wendt (Univ. of Arizona); and J. Dunn (Univ. of Arkansas)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Dept. of Chem Engrg, Univ. of Arizona, Tucson, AZ 85721; and Dept. of Mathematical Sciences, Univ. of Arkansas, Fayetteville, AR 72701		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. 68-02-4701 (Acurex); P.O. 8D1713NATA (Wendt); CR814945 (Dunn)
12. SPONSORING AGENCY NAME AND ADDRESS **EPA, Office of Research and Development** Air and Energy Engineering Research Laboratory **Research Triangle Park, NC 27711**		13. TYPE OF REPORT AND PERIOD COVERED Published paper; 14. SPONSORING AGENCY CODE **EPA/600/13**

15. SUPPLEMENTARY NOTES AEERL project officer is Paul M. Lemieux, Mail Drop 65, 919/541-0962. Presented at 1st Int. Congress on Toxic Combustion Byproducts: Formation and Control, UCLA, Los Angeles, CA, 8/2-4/89.

16. ABSTRACT The paper discusses combining experimental results from a pilot-scale rotary kiln incinerator simulator with a theoretical model in order to explore the potential of minimizing transient emissions through changes in kiln rotation speed and temperature, steady state oxygen enrichment, and oxygen enrichment in a dynamic mode. Results indicate that transient organic emissions can indeed be minimized by changes in these kiln operating parameters but, because of the complex interactions of physical and chemical processes controlling emissions, the appropriate abatement procedures must be implemented carefully. Transient emissions of organics occur from rotary kiln incinerators when drums containing liquid wastes bound on sorbents are introduced in batches. Physical processes controlling the release of waste from the sorbent material are greatly affected by the rotation speed and temperature of the kiln. Local partial pressure of oxygen influences the rate of oxidation of the puff formed inside the kiln. These physical and chemical phenomena can be used to control transient emissions by oxygen enrichment, where it is done in either a steady or a dynamic mode.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Incinerators	Stationary Sources	21B
Kilns	Rotary Kilns	13A 11G
Emission	Liquid Waste	14G
Organic Compounds		07C
Mathematical Models		12A
Wastes		
Combustion		
Sorbents		

18. DISTRIBUTION STATEMENT **Release to Public**	19. SECURITY CLASS *(This Report)* **Unclassified**	21. NO. OF PAGES 26
	20. SECURITY CLASS *(This page)* **Unclassified**	22. PRICE

EPA Form 2220-1 (9-73)

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

EPA/600/D-89/131

MINIMIZATION OF TRANSIENT EMISSIONS FROM ROTARY KILN INCINERATORS

Paul M. Lemieux, William P. Linak, Joseph A. McSorley
Air and Energy Engineering Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Jost O.L. Wendt
Department of Chemical Engineering
University of Arizona
Tucson, AZ 85721

James E. Dunn
Department of Mathematical Sciences
University of Arkansas
Fayetteville, AR 72701

ABSTRACT

Transient emissions of organics occur from rotary kiln incinerators when drums containing liquid wastes bound on sorbents are introduced in a batch-wise fashion. Physical processes controlling the release of waste from the sorbent material are greatly affected by the rotation speed of the kiln and the kiln temperature. Local partial pressure of oxygen influences the rate of oxidation of the puff formed inside the kiln. These physical and chemical phenomena can be exploited to effect control of transient emissions by oxygen enrichment, where this is accomplished in either a steady or a dynamic mode.

Experimental results from a pilot-scale rotary kiln incinerator simulator were combined with a theoretical model in order to explore the potential of minimizing transient emissions through changes in kiln rotation speed, kiln temperature, steady oxygen enrichment, and oxygen enrichment in a dynamic mode. Results indicated that transient organic emissions could indeed be minimized by changes in these kiln operating parameters, but because of the complex interactions of physical and chemical processes controlling emissions, the appropriate abatement procedures must be carefully implemented.

INTRODUCTION

The destruction of liquid hazardous wastes to form innocuous products of combustion is a problem of national importance. Rotary kiln incinerators constitute a sizable fraction of hazardous waste incinerators currently in use in the U.S. (Oppelt, 1987). Rotary kiln incinerators are also unique in that they are designed to allow a portion of their waste load

to be charged in batch rather than continuous mode. In this batch mode of operation, solid wastes and "containerized" liquid wastes are introduced through entrance chutes, typically cocurrent with the gas flow. Bed motion due to kiln angle and rotation speed continuously exposes fresh surface for oxidation, determines the residence times of non-combustible materials, and provides for continuous ash removal. Upon entry into the incinerator, a liquid waste container (typically a cardboard, plastic, or steel drum) ruptures or burns, exposing the contents to the hot kiln environment. The liquid then rapidly vaporizes and reacts with the excess oxygen present in the combustion gases from the continuous primary flame. A possible kiln failure condition arises when the evolution of waste gases from the ruptured container is more rapid than the rate at which the stoichiometric amount of oxygen can be supplied by the combustion gases from the primary flame. This transient overcharging condition, unique to batch mode systems, can lead to a "puff" of incompletely destroyed organic material which must subsequently be destroyed by the system afterburner (Bastian and Wood, 1987; Wood, 1987). Under circumstances when the afterburner cannot destroy the quantity of organic material released, this puff leads to a system failure.

Previous work has focussed on characterizing the conditions under which transient puffs are produced (Linak et al., 1987a, 1987b) and on determination of the hazardous constituents present in the exhaust gases during such a transient upset condition. Formulation of a model (Wendt and Linak, 1988) allowed some of the fundamental physical phenomena important in the generation of puffs to be delineated. Although this model was successful in explaining the effect of kiln rotation speed (RPM), it was less successful in quantifying the effect of kiln temperature (T_k).

The research reported here is concerned not with a description of how transient overcharging conditions are produced, but rather with the determination of practical methods that allow transient puffs from a given waste to be minimized. First, the theoretical model described previously (Wendt and Linak, 1988) was modified. The purpose of these changes was both to better account for the observed effects of temperature and to more realistically describe how kiln rotation exposed new surface for liquid waste release. Second, the model was used to predict the kiln operating conditions under which puffs could be minimized. The predicted optimum conditions suggested the use of oxygen enrichment as a practical means to reduce transient puffs. Experimental data from a laboratory rotary kiln simulator (Figure 1) then confirmed the general predictions of the model, but because oxygen enrichment affects several kiln variables simultaneously, a true optimum in operating conditions is difficult to achieve in practice. Additional experiments in which oxygen enrichment occurred in a dynamic mode did confirm the predicted optimum conditions at which transient emissions were minimized, and suggested a practical technique through which these optimum conditions can be implemented.

Oxygen enrichment has long been applied to many industrial combustion processes in order to increase product yields and thermal efficiency. The use of oxygen in hazardous waste incineration to augment or enrich oxidant levels in the combustion zones has the potential to improve the destruction and removal efficiencies (DREs) of the principal organic hazardous constituents (POHCs), minimize the formation of products of incomplete combustion (PICs), and allow for better control of the combustion process. Results from research reported here indicate how oxygen enrichment could be applied to rotary kiln incinerators in order to minimize transient failure conditions caused by the batch introduction of waste material and why implementation of this technique requires some care.

THEORETICAL PREDICTIONS

Model Development

It is assumed that transient overcharging conditions are controlled by the rate at which waste is evolved from the sorbent aggregate, rather than by the rate at which mixing occurs in the gas phase. This assumption is based on the observation that transient puffs occur over periods of time (0.5 - 2.0 min.) which are much longer than any reasonable mixing time.

Following Wendt and Linak (1988), waste evolution is modeled in two parts, as shown on Figure 2. The first part represents the prototype problem of transient simultaneous heat and mass transfer into and out of a sorbent aggregate layer. The layer, the thickness of which is proportional to the container diameter, is heated from above by radiation from a source at T_k (neglecting convection) and from below, where it is in direct contact with the kiln refractory, by conduction. These thermal boundary conditions differ from those used in previous work.

The second part of the model describes how the rate of surface exposure is influenced by RPM and differs from that presented previously. In the new model, it is assumed that surface renewal occurs every quarter of a revolution, and this was supported by visual observation. At each surface renewal event, the entire aggregate, and not each fragment, breaks up into four new pieces. Thus the surface available for mass transfer increases at the first event, but, although it is renewed at every subsequent event, it no longer increases in value. In the previous model the surface area increased geometrically with fragmentation and the time between events depended on the current aggregate size. The current approach, however, does not attempt to describe the motion of the bed in detail (Zablotny, 1965).

For the vaporization model, the conservation equations to be solved are identical to those presented previously (Wendt and Linak, 1988), but are presented below for the sake of clarity:

Energy:

$$\frac{\partial T}{\partial t} = \frac{k}{(1-\varepsilon)\, C_p\, \rho} \frac{\partial^2 T}{\partial y^2} - \frac{\Delta H_v}{C_p\, \rho} R_v(C,C_s,T) \tag{1}$$

Species in the interstitial gas phase:

$$\frac{\partial C}{\partial t} = D_{eff} \frac{\partial^2 C}{\partial y^2} + (1-\varepsilon)\, R_v(C,C_s,T) \tag{2}$$

Species within/on sorbent particles:

$$\frac{\partial C_s}{\partial t} = -R_v(C,C_s,T) \tag{3}$$

The initial conditions are, as before:

$$t = 0: \qquad T = T_0, \qquad C = C_0, \qquad C_s = C_{s0}. \tag{4}$$

The boundary conditions, which now are different from prior work, are:

$$\begin{aligned} y = 0: \quad & -k\frac{\partial T}{\partial y} = \xi\sigma(T_k^4 - T^4), \qquad C = 0 \\ y = L: \quad & T = T_k, \qquad \frac{\partial C}{\partial y} = 0 \end{aligned} \tag{5}$$

Solution of these equations yields the total mass flux of waste leaving the surface as a function of time. This quantity, multiplied by surface area yields the "Unsatisfied Oxygen Demand," which defines the puff intensity, thus:

$$P^*_{O_2} = P_{O_2} - \nu \frac{F_w}{F_f} \tag{6}$$

$$\begin{aligned} &\text{Unsatisfied Oxygen Demand} = 0 \qquad \text{for } P^*_{O_2} \geq 0 \\ &\text{Unsatisfied Oxygen Demand} = -P^*_{O_2} F_f \quad \text{for } P^*_{O_2} < 0 \end{aligned} \tag{7}$$

The integral of the puff intensity over $0 < t < \infty$ defines the puff magnitude, which is the output from the model. The time interval between surface exposure events is now given by:

$$\Delta t = 0.25 \left(\frac{60}{RPM}\right) \tag{8}$$

Equations 1 through 3 were solved numerically using a fully implicit algorithm and finite differencing with a variable mesh which collapsed at each boundary where gradients were high. (Wendt et al., 1979)

Model Predictions

As before (Wendt and Linak, 1988), the model presented above yielded puff intensity traces which compared well qualitatively with experimental total hydrocarbon traces. The predictions of puff magnitude for toluene surrogate waste, normalized to a selected base case condition, are shown on Figure 3a as a function of T_k and RPM. Clearly, the model predicts an optimum set of operating conditions for minimizing puff magnitude. This optimum point occurs at the lowest T_k and the lowest RPM possible. In practice, the lowest practicable rotation speed was 0.5 rpm since some rotation is desirable in order to let the waste evolve over a reasonable period of time. Waste, sorbent, and kiln parameters used to calculate results at the base case conditions for toluene are presented in Table 1.

Equation 6 suggests that an increase in post primary flame oxygen partial pressure (P_{O_2}), achievable through oxygen enrichment, should also help to further minimize puff intensity. However, oxygen enrichment in general is accompanied by changes in T_k, due to higher adiabatic flame temperatures. Figure 3b shows predictions of puff magnitude as a function of T_k and P_{O_2} holding total flue gas flow rate (F_f) and RPM constant (RPM has been set to its lowest limiting practical value of 0.5 rpm). Again, in contrast to Wendt and Linak (1988), we now predict a large effect of T_k. The optimum condition for minimum puff magnitude, however, occurs at the lowest T_k and the highest P_{O_2} possible. The next step is to determine the extent to which these predictions are substantiated by experimental data.

EXPERIMENTAL APPROACH

Apparatus

The EPA rotary kiln incinerator simulator has been described in detail previously (Linak et al., 1987a, 1987b). It has been established that the 73 kW (250,000 Btu/hr) pilot-scale simulator exhibits the salient features of full-scale units with thermal ratings 20 to 40 times larger. The simulator matches the volumetric heat release, gas-phase residence time, and temperature profile of many full-scale units, and yet is flexible enough to allow parametric testing. A schematic drawing of the simulator is presented in Figure 1.

The water-cooled prototype burner is designed to produce stable flames utilizing oxidant streams ranging from 22 to 100 percent oxygen. The burner provides for separate introduction of natural gas, air, and oxygen with turndown ratios of at least 1 to 10. The

burner is easily ignited and capable of rapid response to changes in the fuel, air, or oxygen flows.

Containerized batch charges are introduced through a sliding gate/ram assembly located downstream of the continuous natural-gas-fired oxygen-enriched burner as shown in Figure 1. Quantification of the transient puff produced requires the real-time measurement of system response variables. These dependent variables include peak responses of O_2, CO, CO_2, NO_x, and total volatile hydrocarbon (THC) concentrations measured by continuous flame ionization detection (FID) and reported in equivalent parts per million methane. Other dependent variables include the time-integrated responses of the CO and THC analyzers and particulate filter weight. At constant sampling conditions, these variables are proportional to the total mass emitted in the transient puff. Tared quartz filters and the heated particulate filter system upstream of the THC analyzer were used to collect particulate samples. Volatile hydrocarbons are defined as those in the gas-phase at 420 K (300 °F), the temperature of the heated sample line.

Charges to the kiln consisted of varying amounts (50 to 200 g, 0.11 to 0.44 lb) of toluene or No. 5 fuel oil on 135 g (0.30 lb) of ground corncob sorbent sealed in a 45 g (0.10 lb) cylindrical uncoated 1 qt (0.95 L) cardboard container. The majority of these tests, however, examined nominal "waste" loadings of 100 g (0.22 lb). Toluene and No. 5 fuel oil were chosen because together they span a wide range of "waste" viscosities, yield large chlorine-free puffs to which the FID is very sensitive, and produce large particulate loadings. Nominal charge masses of 100 g (0.22 lb) were chosen so as to produce large transients which did not exceed the FID linear response region of zero to 10,000 ppm (reported as methane) and to approximate the range of volumetric waste heat release rates that would be typical when introducing liquid charges into a full-scale kiln.

There are difficulties associated with the measurement of puff intensity and puff magnitude (Linak et al., 1987b) since no single on-line measurement (such as THC) represented those quantities for all surrogate wastes under all conditions examined. For toluene on sorbent, it was found that, while THC traces might represent puff intensities if these were low, the total filter sample representing total soot loading in the puff was a better indicator of puff magnitude over the entire range of conditions examined. For carbon tetrachloride on sorbent, CO was the best indicator, while both THC and the total filter weight seemed adequate for the less volatile No. 5 fuel oil. In this paper the focus is on toluene and No. 5 fuel oil and therefore it is assumed that THC traces properly represent instantaneous puff intensities provided these are relatively low, and that total filter loadings represent puff magnitudes (integrated puff intensities over the puff duration) over the entire range of parameters examined.

Parametric Testing

Three sets of experiments were conducted. Test Set 1 focussed on determination of puff magnitude without any oxygen enrichment; Test Set 2 focussed on the effects of oxygen enrichment introduced in a steady-state mode; and Test Set 3 focussed on oxygen enrichment introduced in a pulsed, dynamic mode. The purpose of Test Sets 1 and 2 was to validate the model predictions, while that of Test Set 3 was to demonstrate how the predicted methods for minimizing puffs can be reduced to practice.

Test Set 1 (Linak et al., 1987b) allowed variation of charge mass (MASS), RPM, and T_k as independent primary variables. Oxygen enrichment was not used for these tests. Operating conditions were:

(a) Surrogate wastes: toluene, carbon tetrachloride, methylene chloride, and No.5 fuel oil.
(b) Auxiliary gas flow rate, 5.66 sm^3/h (200 scfh).
(c) Air flow rate, 109.0 sm^3/h (3850 scfh).
(d) Oxygen flow rate, 0 sm^3/h (0 scfh).
(e) Stoichiometric ratio, 2.0 (inverse equivalence ratio).

Data from Test Set 1 were taken from 24 trials (each involving between 5 and 15 replicate charges).

Test Set 2 (Linak et al., 1988) consisted of determination of puff magnitude for a given surrogate waste amount (MASS = 100 g) and at a fixed RPM (0.5 rpm) as a function of T_k, P_{O_2}, and F_f. These last three parameters can be considered as derived quantities, and were varied according to an experimental design in which oxygen flow rate, air flow rate, and kiln firing rate (natural gas load) constituted the experimentally adjustable independent variables. Clearly the derived variables are not independent, since T_k and P_{O_2} are directly correlated. For this test series, the ranges of operating variables investigated were:

(a) Surrogate waste: toluene
(b) Auxiliary gas flow rate, 4.25 to 7.08 sm^3/h (150 to 250 scfh).
(c) Air flow rate, 35.4 to 160.2 sm^3/h (1249 to 5656 scfh).
(d) Oxygen flow rate, 1.13 to 9.91 sm^3/h (40 to 350 scfh).
(e) Stoichiometric ratio, 1.3 to 2.7.

Twenty one trials, each involving 10-12 replicate charges, constituted this test set.

For both Test Sets 1 and 2, portions of the experimental design followed previous procedures and were based on response surface experimentation (Hicks, 1973). This methodology allows, on the basis of one experiment involving a minimal number of trials, determination of an empirical relationship between the response and the controlled variables within the experimental region. Since P_{O_2} and T_k are not independent, individual effects of

these two parameters on puff magnitude could be determined only through statistical analysis. In fact, the optimum operating point for minimization of puffs, corresponding to high P_{O_2} and low T_k at fixed F_f, could not be accessed experimentally using oxygen enrichment under steady-state conditions.

Test Set 3 was designed to allow the optimum operating point for minimization of puffs to be accessed experimentally. This third set attempted to physically separate the individual effects of P_{O_2} and T_k. To accomplish this, the oxygen delivery system was modified to allow for a timed pulse of additional pure oxygen. By incorporating dynamic oxygen control, additional oxygen could be added to the kiln only when needed during "waste" addition. Dynamic oxygen control utilizes the thermal inertia of the kiln refractory to minimize the accompanying increases in the kiln refractory temperature which occurred during steady-state oxygen addition. This allowed semi-independent control of both T_k and P_{O_2}. The conditions for Test Set 3 were:

(a) Surrogate waste: No. 5 fuel oil
(b) Auxiliary gas flow rate, 5.66 sm^3/h (200 scfh).
(c) Air flow rate, 85.0 to 135.9 sm^3/h (3000 to 4800 scfh).
(d) Oxygen flow rate, 1.13 sm^3/h (40 scfh) base, pulsed to 5.66 sm^3/h (200 scfh).
(e) Stoichiometric ratio, 2.0 base, pulsed to 2.5.

The following kiln parameters were held constant for all tests:

(a) Burner position, -0.34 m (-13.5 in.) inside front kiln wall.
(b) Kiln pressure, -37.4 Pa (-0.15 in. H_2O).
(c) Sample port at position 4 (See Figure 1).

RESULTS AND DISCUSSION

Experimental results are reported in terms of puff magnitude, represented by filter weight, and normalized for the base case condition depicted on Table 1. In this way, experimental results can be compared to theoretical predictions. Since the focus of this research is determination of methods of minimizing puffs from a given amount of waste, an obvious result (from Test Set 1) which showed that lower waste masses resulted in smaller puffs (Linak et al., 1987b) is not discussed here.

Test Set 1 data could be correlated (for toluene waste, $r^2=0.999$) by an empirical expression of the form:

$$\text{Puff Magnitude} = \exp[a + b(RPM) + c(MASS)(T_k) + d(T_k) + e(MASS)] \quad (9)$$

where a through e are constants. This expression can be plotted as a response surface, normalized to base case conditions. Figure 4 shows such a surface plotted as a function of RPM and T_k for constant MASS (100 g). Comparison with Figure 3a shows good qualitative and fair quantitative agreement between predictions and experimental data, indicating that the model is valid. Figures 3a and 4 show that transient puffs can be minimized by operating at low RPM and low T_k. Therefore, subsequent tests focussed on low values of RPM (0.5 rpm).

The use of oxygen enrichment in Test Set 2, and the resulting variations in F_f between different trials necessitated proper correction of the raw data to account for the obvious dilution effects. This was accomplished by correcting all measured puff magnitudes to an F_f of 113.3 sm^3/h (4000 scfh). However, F_f is still an important secondary variable because, together with P_{O_2}, it determines the supply of oxygen to the waste. Corrected data were correlated ($r^2 = 0.757$) by an empirical expression of the form:

$$\text{Puff Magnitude} = a' + b'(T_k) + c'(P_{O_2}) + d'(T_k)^2 + e'(P_{O_2})(T_k) + f'(P_{O_2})^2 + g'(F_f) \quad (10)$$

where a' through g' are constants. This expression can be used to predict puff magnitude within the range of the variables investigated even though specific combinations of these three variables (T_k, P_{O_2}, and F_f) may not be achievable in practice under steady-state conditions. Figure 5 presents a normalized response surface for puff magnitude as a function of T_k and P_{O_2}, with F_f held constant (113.3 sm^3/h, 4000 scfh). Figure 5 can be compared directly with theoretical predictions (Figure 3b), and again shows good semi-quantitative agreement between theory and experiment. Both theory and experiment predict an optimum operating point for minimum puff magnitude at high P_{O_2} and low T_k. However, it must re-emphasized that use of steady-state oxygen enrichment prohibits practical attainment of this optimum.

As described above, use of timed pulsed pure oxygen addition for Test Set 3 partially decouples T_k and P_{O_2} and allows the predicted optimum to be more readily attained. Four trials involving 10 replicate charges each were conducted examining the following conditions:

(a) SR=2.0, T_k = 1250 K, P_{O_2} = 0.115
(b) SR=2.0, T_k = 1300 K, P_{O_2} = 0.115
(c) SR=2.0, T_k = 1250 K, P_{O_2} = 0.164
(d) SR=2.0, T_k = 1200 K, P_{O_2} = 0.164

These data were corrected for dilution and correlated to a simple linear empirical model ($r^2 = 0.999$) in terms of P_{O_2} and T_k. Figure 6 presents these data as a response surface after normalization to the base case condition. The data indicate that minimum T_k and maximum P_{O_2} did in fact result in the smallest measured puff magnitude.

In order to validate the use of filter weight (taken upstream of the THC analyzer) as a surrogate indicator of emissions of combustion by-products, it is instructive to compare this easily measured quantity to an EPA standard method for measuring particle loading in stack gases. Figure 7 shows particle loading as measured by a modified Source Assessment Sampling System (SASS) (U.S. EPA, 1986) fitted to a linear empirical model and corresponding to the four trials examined by Test Set 3. There is good qualitative and quantitative agreement between the normalized samples.

Table 2 presents the effects of oxygen concentration and temperature on the organic products of incomplete combustion, as measured by the modified SASS method for Test Set 3. The organics collected in the SASS sampling train are characterized by their boiling points into two fractions, total chromatographable organics (TCO) and gravimetric organics (GRAV). The TCO range typically contains semi-volatile organics with boiling points between 100 and 300°C (212 and 572°F). The GRAV range consists primarily of non-volatile organics with boiling points >300°C (572°F). Compounds in the TCO range can often be identified using GC/MS techniques. Polycyclic aromatic hydrocarbons (PAHs) and many organics that are believed to be of a carcinogenic, toxic, or mutagenic nature fall into both the TCO and GRAV ranges. Table 2 depicts total particle, TCO only, GRAV only, and total organic extract (TCO + GRAV) concentrations, respectively. The total organic extract (TCO + GRAV, typically 0.1-10% of SASS filter mass) tracks the SASS filter and THC filter loading results (see Figures 6 and 7). While Table 2 shows the TCO fraction to have a strong dependence on both T_k at constant P_{O_2} and P_{O_2} at constant T_k, the GRAV fraction is less dependent on T_k but strongly dependent on P_{O_2}. This suggests that the more volatile fraction of the PICs is that fraction least likely to be minimized by the steady-state addition of oxygen where the higher temperatures would tend to release more volatile organics. The GRAV data suggest that higher oxygen levels are very effective at minimizing emissions in the GRAV range.

CONCLUSIONS

Transient puffs can be minimized through operating a rotary kiln at low rotation speed and low temperature. Further improvement can be accomplished by the the use of oxygen enrichment. However, oxygen augmentation must be applied so as not to allow significant temperature increases. One method of accomplishing this is to apply this technique in a timed pulsed, dynamically controlled mode.

A simple direct measurement of puff magnitude using filter weight from a slipstream of the flue gas is representative of the mass emissions during the transient upsets for the high Btu surrogate wastes examined.

Methods of minimizing toxic transient emissions can be explored through the use of a model which requires only two unknown parameters. The model yielded results that agreed well with experimental data. Future work will attempt to refine the model and expand its use as a tool to rank liquid wastes with respect to their propensity to form transient overcharging conditions.

NOMENCLATURE

C	Concentration in interstitial gas phase (gmole/cm^3)
C_0	Initial concentration in interstitial gas phase (gmole/cm^3)
C_{crit}	Critical concentration defining falling drying rate (gmole/cm^3 sorbent)
C_s	Concentration in sorbent (gmole/cm^3 sorbent)
C_{s0}	Initial concentration in sorbent (gmole/cm^3 sorbent)
C_p	Specific heat of sorbent (cal/g K)
d_g	Sorbent grain diameter (cm)
D_i	Aggregate diameter (cm)
D_{eff}	Effective diffusivity (cm^2/s)
D_m	Molecular diffusivity (cm^2/s)
F_f	Molar or volumetric flow of flue gas (gmole/s or scfh)
F_w	Mass flow of waste out of surface (g/s)
ΔH_v	Waste latent heat of vaporization (cal/gmole)
k	Thermal conductivity of sorbent (cal/s cm K)
L	Characteristic length, cm
MASS	Charge mass (g)
MW	Molecular weight (g/gmole)
P/P_{base}	Relative puff magnitude (puff magnitude normalized by base case puff magnitude)
$P_{O_2}^*$	Quantity defined by Equation (6)
P_{O_2}	Oxygen mole fraction in flame flue gas
P_{vap}	Vapor pressure of waste (atm)
$Q_{cond}(t)$	Conductive heat flux through sorbent aggregate (cal/cm^2 s)
$Q_{rad}(t)$	Radiative heat flux into sorbent aggregate (cal/cm^2 s)
R_v	Vaporization rate (gmole/cm^3 s)
RPM	Kiln rotation speed (rpm)
T	Temperature (K)
T_0	Initial temperature (K)
T_b	Normal boiling point (K)
T_k	Kiln temperature (K)
T_m	Measured temperature at kiln exit (K)

t	Time (s)
Δt	Time interval between surface renewal events (s)
$W(t)$	Mass flux out of sorbent aggregate (g/cm^2 s)
y	Distance into sorbent aggregate (cm)

Greek Symbols

ε	Bulk porosity
ξ	Emissivity
ν	Stoichiometric oxygen requirement of waste (gmole O_2 required/g waste)
ρ	Sorbent density (g/cm^3)
σ	Stefan-Boltzmann constant (1.355×10^{-12} cal./s cm^2 K)

ACKNOWLEDGEMENTS

Portions of this work were conducted under EPA Contract 68-02-4701 with Acurex Corporation, EPA Purchase Order 8D1713NATA with J.O.L. Wendt, and EPA Cooperative Agreement CR-814945-01-0 with University of Arkansas (J.E. Dunn). The authors would like to thank EPA/AEERL's Bill Lowans and Ray Grote, who operated the rotary kiln and sampling equipment and Acurex's Jeff Ryan, who performed the analytical work. The authors would also like to thank Robert Hall, Chief, Combustion Research Branch, AEERL, for his support. The authors would like to acknowledge the contribution of American Combustion, Inc., of Norcross, GA, who designed, fabricated, and installed a prototype version of their Pyretron burner on EPA's rotary kiln incinerator simulator. Additionally, the authors would like to acknowledge the contribution of Liquid Air Corp., of Countryside, IL, who provided a portion of the liquid oxygen for the tests. Finally, the authors would like to thank the EPA Superfund Innovative Technology Evaluation (SITE) program for partial support of this work.

DISCLAIMER

The research described in this article has been reviewed by the Air and Energy Engineering Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. The contents of this article should not be construed to represent Agency policy nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

REFERENCES

Bastian, R.E. and Wood, R.W., (1987), Eastman Kodak Company Chemical Waste Incineration Organic Compound Destruction, *Proceedings on Rotary Kiln Incineration of Hazardous Waste*, pp. 80, Baton Rouge, LA.

Foley, K.M., (1978), *Chemical Properties, Physical Properties and Uses of the Andersons' Corncob Products*, 2nd ed., The Andersons, Maumee, OH.

Handbook of Chemistry and Physics, (1982), Weast, R.C. and Astle M.J. eds., 63rd ed., CRC Press Inc, West Palm Beach, FL.

Hicks, C.R., (1973), *Fundamental Concepts in the Design of Experiments*, 2nd ed., Holt, Rinehart and Winston Inc., New York, NY.

Linak, W.P., Kilgroe, J.D., McSorley, J.A., Wendt, J.O.L. and Dunn, J.E., (1987a), On the Occurrence of Transient Puffs in a Rotary Kiln Incinerator Simulator I. Prototype Solid Plastic Wastes, *J. Air Poll. Cont. Assoc.*, 37, 54.

Linak, W.P., McSorley, J.A., Wendt, J.O.L. and Dunn, J.E., (1987b), On the Occurrence of Transient Puffs in a Rotary Kiln Incinerator Simulator II. Contained Liquid Wastes on Sorbent, *J. Air Poll. Cont. Assoc.*, 37, 934.

Linak, W.P., McSorley, J.A., Wendt, J.O.L. and Dunn, J.E., (1988), Rotary Kiln Incineration: The Effect of Oxygen Enrichment on Formation of Transient Puffs During Batch Introduction of Hazardous Wastes, *Proceedings of the Fourteenth Annual Research Symposium on Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste*, Cincinnati, OH.

Oppelt, E.T., (1987), Incineration of Hazardous Waste A Critical Review., *J. Air Poll. Cont. Assoc.*, 37, 558.

Reed, R.J., (1978), *North American Combustion Handbook*, 2nd ed., North American Manufacturing Co., Cleveland, OH.

U.S. EPA (1986), *Test Methods for Evaluating Solid Waste*, SW846, Method 0020.

Wendt, J.O.L. and Linak, W.P., (1988), Mechanisms Governing Transients from the Batch Incineration of Liquid Wastes in Rotary Kilns, *Combst. Sci. and Tech.*, 61, 169.

Wendt, J.O.L., Martinez, C.M., Lilley, D.M. and Corley, T.L., (1979), Numerical Solution of Stiff Boundary Valued Problems in Kinetics and Diffusion, *Chem. Eng. Sci.*, 34, 527.

Wood, R.W., (1987), Eastman Kodak Company Rotary Kiln Performance Testing, *Proceedings on Rotary Kiln Incineration of Hazardous Waste*, pp. 105, Baton Rouge, LA.

Zablotny, W.W., (1965), The Movement of the Charge in Rotary Kilns, *J. Intl. Chem. Eng.*, 5(2), 360.

Table 1. Waste, sorbent, and kiln parameters used to predict the base case puff magnitude.

Waste Parameters (toluene)

MASS	100.0 g
MW	92.0 g/gmole
T_b	383.6 K
ΔH_v	7688.44 cal/gmole
P_{vap} at 298 K	0.05516 atm
P_{vap} at 1250 K	1087.0 atm
Collision diameter	5.27 Å
D_m	0.07330 cm^2/s
ν	0.098 gmole O_2 required/g waste
C_0	2.257E-06 gmole/cm^3
C_{s0}	4.026E-03 gmole/cm^3 sorbent

Sorbent Parameters

Sorbent mass	135.0 g
ρ	0.5 g/cm^3
k	1.96E-04 cal/s cm K
C_p	0.172 cal/g K
ε	0.737
d_g	0.3 cm
D_{eff}	0.03981 cm^2/s
C_{crit} (defines falling rate)	0.001 gmole/cm^3 sorbent
Container diameter	8.9 cm
Container length	16.5 cm

Assume: Sorbent properties are those of sawdust when corncob properties are unavailable. Each aggregate forms four pieces at each surface renewal event every 0.25 revolution.

Kiln Parameters

T_k	1250 K
T_0	298 K
RPM	0.5 rpm
F_f	1.331 gmole/s
P_{O_2}	0.12

Waste and sorbent parameters taken from Foley (1978), Reed (1978), and Weast and Astle (1982).

Table 2: Summary of SASS data for Test Set 3.

Trial	P_{O_2}	T_k (K)	SASS Particulate (mg/m3)	TCO (mg/m3)	GRAV (mg/m3)	TCO+GRAV (mg/m3)
1	0.116	1250	161.9	2.70	27.07	29.77
2	0.135	1150	19.63	1.27	17.83	19.11
3	0.164	1250	18.79	0.394	15.42	15.79
4	0.164	1300	221.59	3.09	19.91	22.92

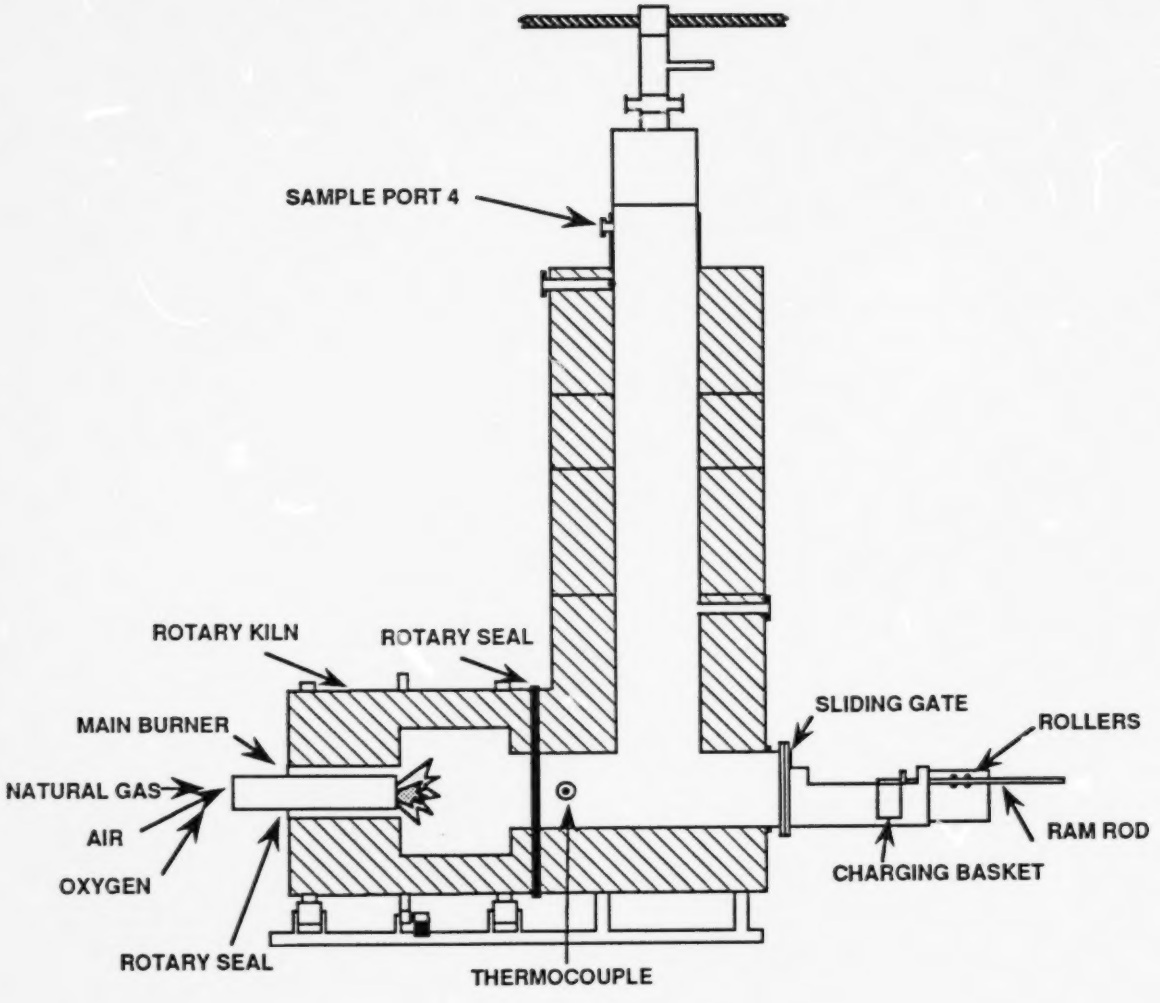
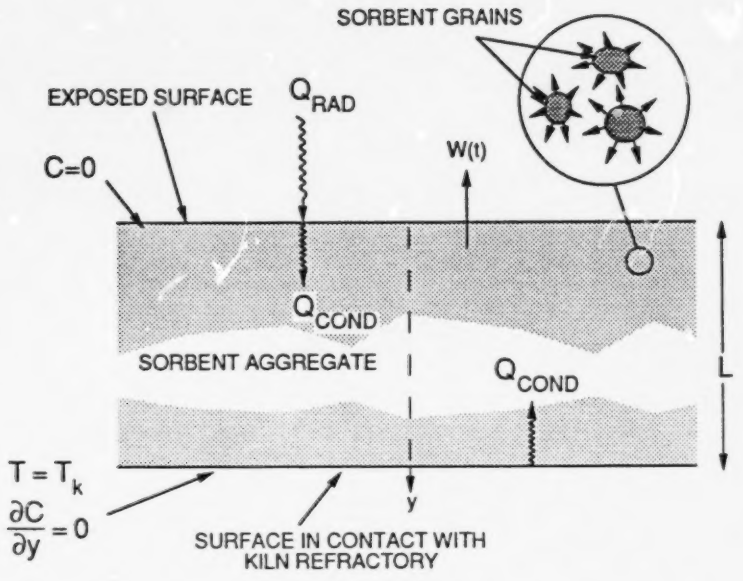


Figure 1: EPA rotary kiln incinerator simulator.

a. VAPORIZATION MODEL



b. SURFACE EXPOSURE MODEL

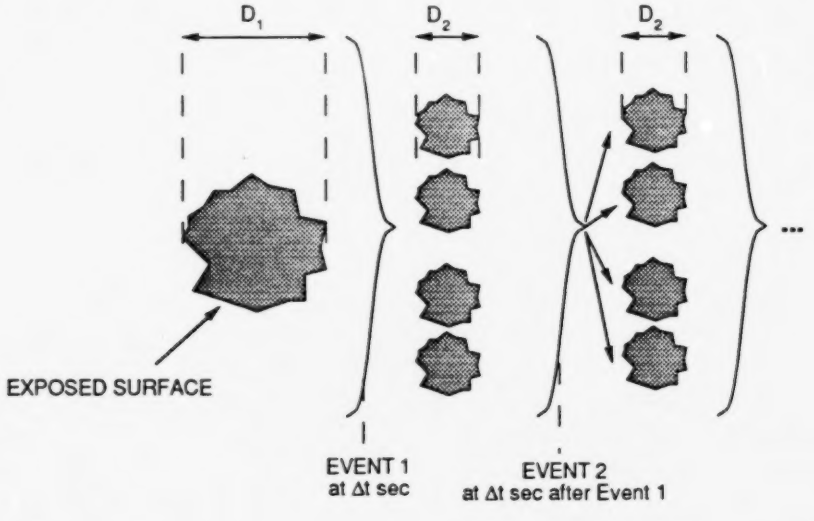
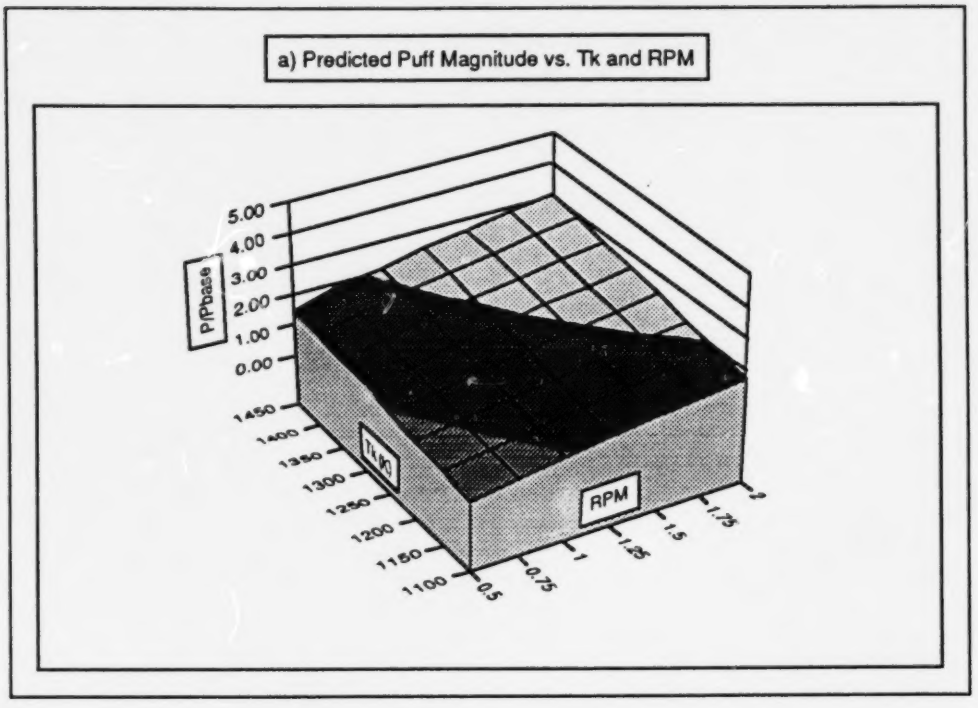


Figure 2: Prototype (a) vaporization and (b) surface exposure models.



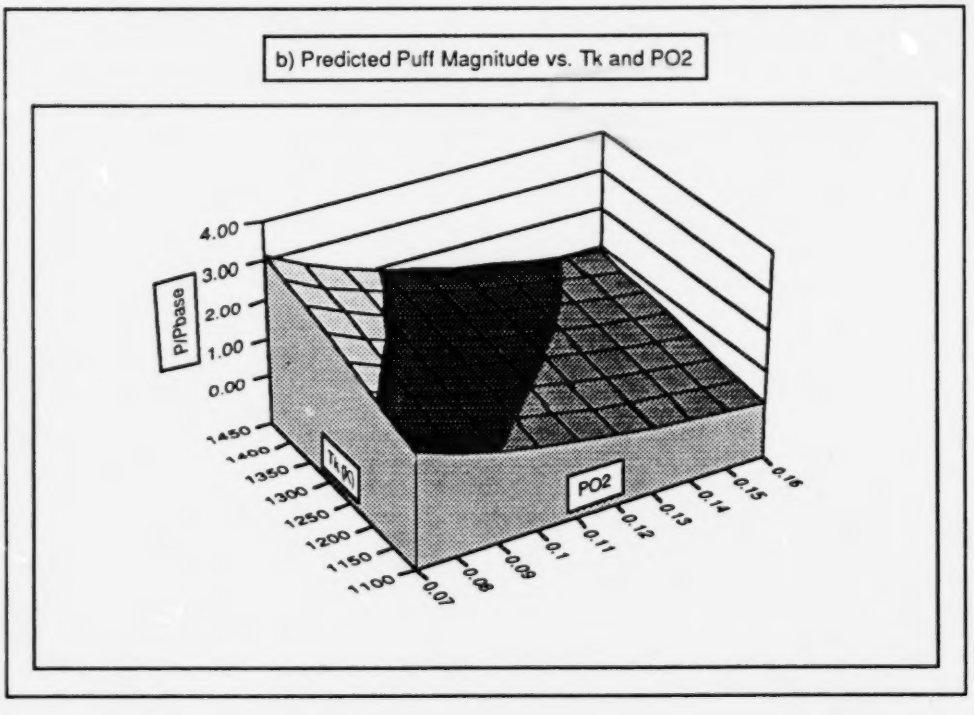


Figure 3: Model Predictions: (a): Predicted effect of T_k and RPM on puff magnitude, normalized to base case conditions of T_k = 1250 K, RPM = 0.5 rpm, at constant MASS = 100 g and P_{O_2} = 0.12. (b): Predicted effect of T_k and P_{O_2} on puff magnitude, normalized to base case conditions of T_k = 1250 K, P_{O_2} = 0.12, at constant MASS = 100 g and RPM = 0.5 rpm, surrogate waste: toluene.

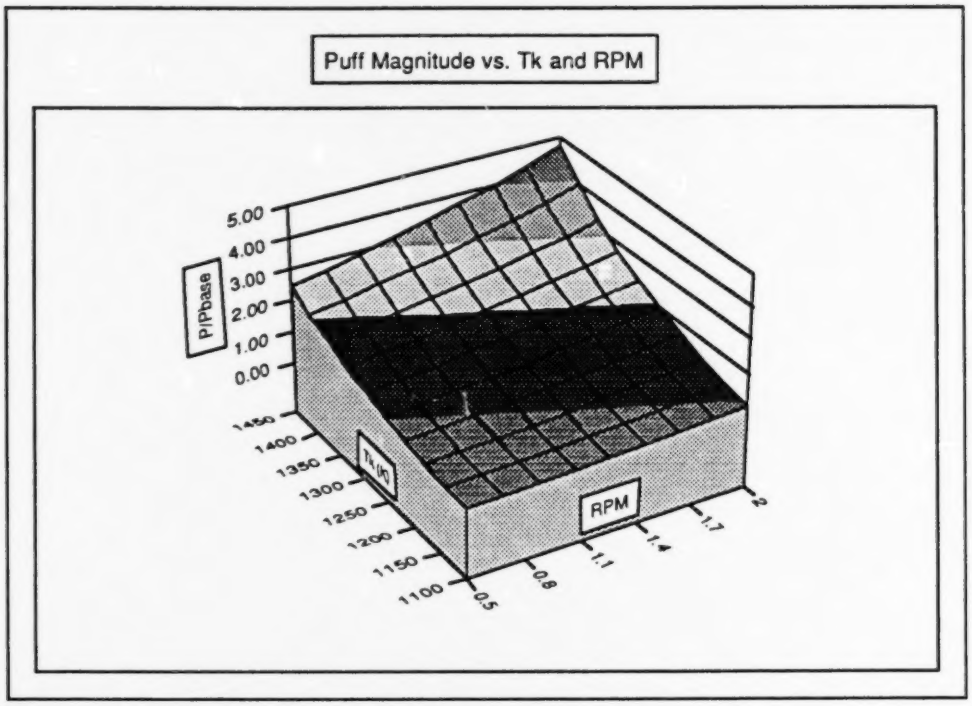


Figure 4: Measured effect of T_k and RPM on puff magnitude, normalized to base case conditions of T_k = 1250 K, RPM = 0.5 rpm, at constant MASS = 100 g and P_{O_2} = 0.12, surrogate waste: toluene.

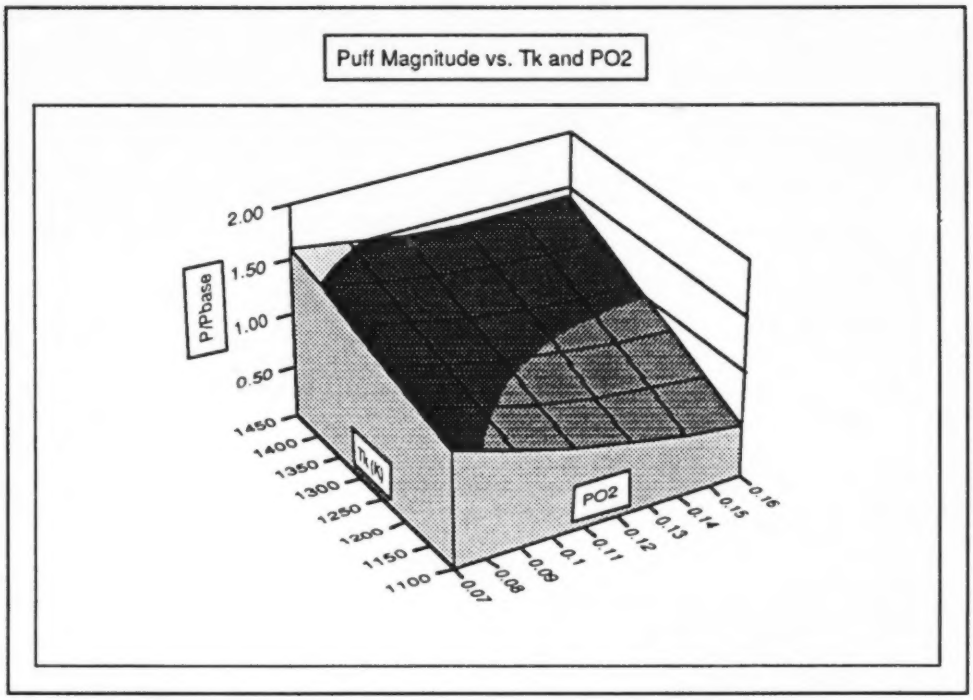


Figure 5: Measured effect of T_k and P_{O_2} on puff magnitude, from Test Set 2 (steady-state oxygen enrichment), normalized to base case conditions of T_k = 1250 K, P_{O_2} = 0.12, at constant MASS = 100 g and RPM = 0.5 rpm, surrogate waste: toluene.

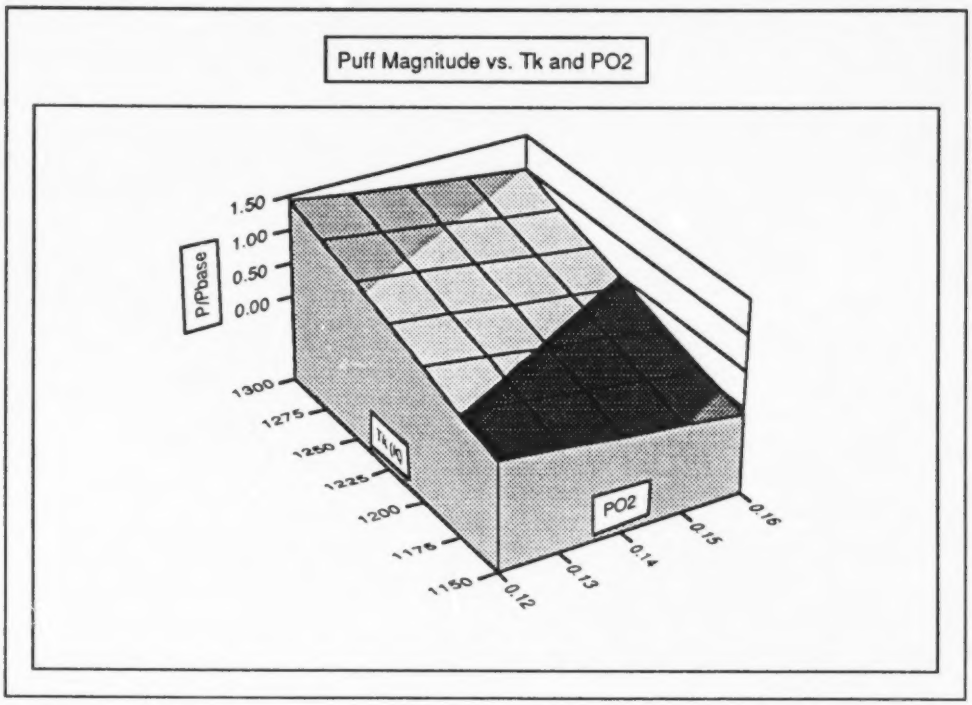


Figure 6: Measured effect of T_k and P_{O_2} on puff magnitude, from Test Set 3 (dynamic oxygen enrichment), normalized to base case conditions of T_k = 1250 K, P_{O_2} = 0.12, at constant MASS = 100 g and RPM = 0.5 rpm. Puff magnitude based on THC filter weights, surrogate waste: No. 5 fuel oil.

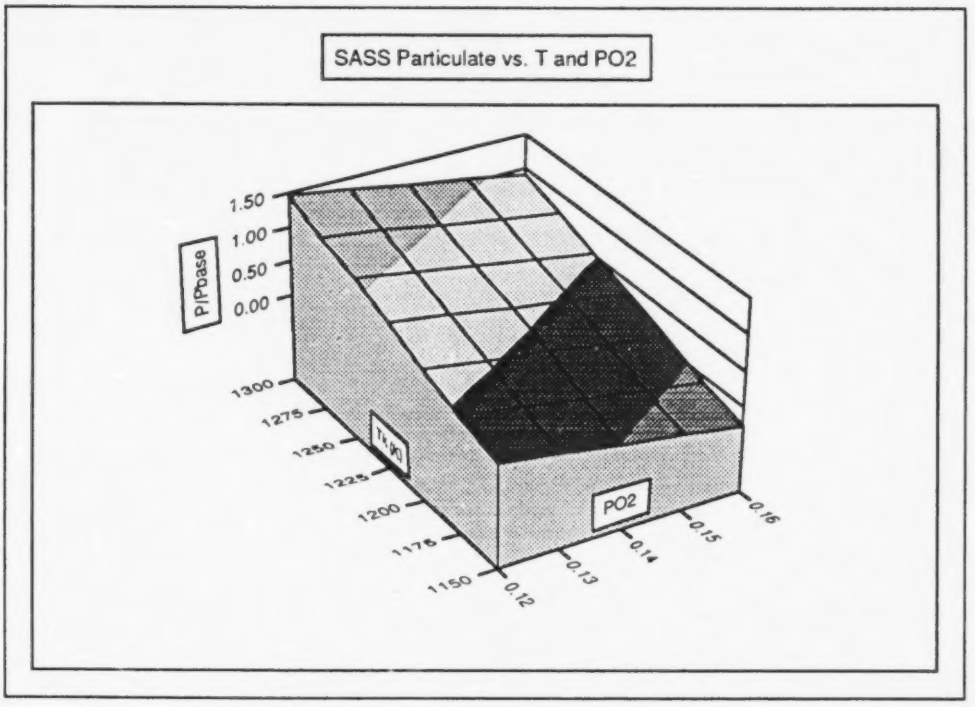


Figure 7: Measured effect of T_k and P_{O_2} on puff magnitude, from Test Set 3 (dynamic oxygen enrichment), normalized to base case conditions of T_k = 1250 K, P_{O_2} = 0.12, at constant MASS = 100 g and RPM = 0.5 rpm. Puff magnitude based on SASS filter weights, surrogate waste: No. 5 fuel oil.